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Meeting global land restoration and protection targets: What would the world look like in 2050?

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ABSTRACT

Land restoration has received increased attention recently as a tool to counteract negative externalities of unsustainable land management on human well-being. This is reflected in targets of the Sustainable Development Goals (SDGs), the Convention on Biological Diversity (CBD), the United Nations Framework of the Convention on Climate Change (UNFCCC) and the United Nations Convention to Combat Desertification (UNCCD). However, the implications of these targets for land use, especially considering their potential conflict with growing food production demands, are largely unexplored. We study the potential and aggregated consequences of meeting these targets on land cover and land system change. We do so by analyzing targets originating from these global commitments towards land restoration and protection and implement them in a global land system change model. We compare this Restoration and Protection scenario with simulation results of two plausible pathways of socio-economic development in the absence of these targets, following the Shared Socio-Economic Pathway (SSP) storylines. We find that meeting global land restoration and protection targets would increase global tree cover by 4 million km^2, increasing forest carbon stocks by 50 Gt and protecting 28% of the terrestrial area with the highest value of both biodiversity and carbon storage. Gains in tree cover and natural land systems would cause a contraction of crop, pasture- and bare land. This results in further cropland intensification and the expansion of land systems that are combining land use demands in mosaics of forest and agriculture. Without these targets, land system architecture tends to become more specialized, while many carbon and biodiversity hotspots, such as in the Americas, India, and Indonesia would be lost. Grassland-agriculture mosaics were threatened by land use change under all scenarios, requiring greater consideration in research and environmental policy. Our results emphasize the need for targeted land management in line with the analyzed policy targets if global restoration and protection targets are to be achieved.

1. Introduction

Human activity has become the major cause of earth system change. Unsustainable land management, exacerbated by climate change, has led to land degradation and desertification, the alteration of carbon, nitrogen and water cycles, and to changes in biodiversity and soil productivity (Steffen et al., 2015). Land degradation is a major driver of ecosystem function and services loss. Vegetation cover and soil nutrient losses reduce soil productive capacity, impacting food-security, health, and other components of human well-being (Lal, 2015; Rojas et al., 2016). During the last century, land degradation has been accelerating through land use pressures such as agricultural expansion and intensification, unsustainable livestock production and urban expansion (WHO, 2017).

Projected increases in world population, lifestyle changes and associated changes in consumption demands will pose additional pressures on land. This has raised awareness about the need to increase land use efficiency and to adopt sustainable land management practices to ensure the provision of food, water, and other ES to future generations (FAO, 2017; Godfray et al., 2010). The central role of land use in achieving sustainable development has been highlighted by the United Nations Sustainable Development Goals (SDGs) that prioritize environmental sustainability as a way to achieve other development goals, such as the alleviation of poverty and hunger (UN, 2015). In particular target 15 *"Life on Land"* has been devoted to the protection, restoration and sustainable use of terrestrial ecosystems.

The implementation of this target is supported by several international conventions and their commitments including the Convention on

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Biological Diversity (CBD) Aichi Biodiversity Targets (CBD, 2011), the United Nations Framework Convention on Climate Change (UNFCCC) target to Reduce Emissions from Deforestation and Forest Degradation (REDD+) (UN-REDD, 2015), as well as the United Nations Convention to Combat Desertification (UNCCD) Land Degradation Neutral target (UNCCD, 2012). These commitments aim to enhance food security, biodiversity conservation, and climate change mitigation through the sustainable management of forests, combating desertification, and halting and reversing land degradation.

As a means of implementing these international commitments at national and regional scales, the Bonn Challenge has been established by the Global Partnership on Forest Landscape Restoration (GPFLR). This Global Restoration Initiative, together with the New York Declaration on Forests, has set the target to restore 350 million ha of deforested and degraded land in the process of agroforestry and forest landscape restoration by 2030 (IUCN, 2017b; UN, 2014). The main rationale of this initiative is to simultaneously improve ecological integrity and human well-being through multi-functional landscapes (GPFLR, 2016a). To support countries in identifying potential areas that would help to meet this aspiration a global map of forest landscape restoration opportunities has been developed (Laestadius et al., 2011). According to this study, more than 2 billion ha of land offer opportunities for forest and landscape restoration, while 156 million ha are already being restored (IUCN, 2017b).

Increased prominence of land restoration and protection in the policy arena (Chazdon, 2008; Chazdon et al., 2017; Aronson and Alexander, 2013) and ongoing interventions across the world (e.g. Afr100, 2017; GPFLR, 2016b) suggest that land restoration and protection will become more important drivers of land use change in the future. This includes the restoration of degraded forest and dryland, and the protection of areas for biodiversity conservation, carbon sequestration and other ecosystem services (ES). These claims will put additional demand on land use that need to be aligned with increasing demand for agricultural production and housing.

While the influence of demand for biodiversity conservation and carbon sequestration on global land use has been assessed (Eitelberg et al., 2016) the relative influence of land restoration and protection targets on land system change and potential impacts of these targets on ES provision has so far remained unexplored. In this context we pose the following questions:

- *How could the implementation of restoration and protection targets drive land system change until 2050?*
- *What is the importance of these targets for the conservation of biodiversity and carbon hotspots until 2050?*

To answer these questions, we first synthesize and cluster global policy targets that focus on land restoration and protection (Section 2.1). We then translate these targets (Section 3.2) into a global scale land system change model (CLUMondo, Section 2.2). Using the SSP1: *"Sustainability"* storyline as a basis, we build a Restoration and Protection scenario and compare it with two reference scenarios that do not consider the implementation of these targets; the SSP1, and the SSP2 *"Middle of the Road"* scenario (O'Neill et al., 2014). We discuss potential implications of meeting global land restoration and protection targets and illustrate the challenges when translated into action on land use (Section 5).

2. Material and models

2.1. Review, synthesis and clustering of targets

Review and synthesis

We first identified global policy targets that focus on the restoration and protection of land-based ES (up to July 2016). Most important in this context is the United Nations Sustainable Development Goal 15 (UN, 2015), that is translated into more explicit policy targets by the three main Rio conventions: the CBD (Aichi target 5, 11, 14, 15) (CBD, 2011), UNCCD (Rio land degradation neutral goal) (UNCCD, 2012), and the UNFCCC (REDD + goal). Next to these commitments, the Bonn Challenge was considered. This global policy initiative is the largest action-oriented platform for forest restoration and has been recognized as a key driver in forest landscape restoration (IUCN, 2017a).

Secondly, we disassembled and interpreted the individual targets by studying their definitions of terms, such as land degradation or restoration, to evaluate the implications of the targets for land use and management [Appendix A]. We then checked if technical rationales and indicators for the individual targets were specified by the conventions. If these were available, we gathered spatial and statistical data which best suited the conventions' definitions or recommended indicators. If targets were not specific enough, we made assumptions in alignment with their description to allow their implementation into land change modelling [Appendix A, Table A. 2]. In case there was neither sufficient data nor specification possible, targets were excluded from further analysis. Similarly, we evaluated the possibility of translating these targets into model settings. Targets that could not be accurately accounted for by adapting model settings were excluded from consideration (Fig. 1).

Clustering

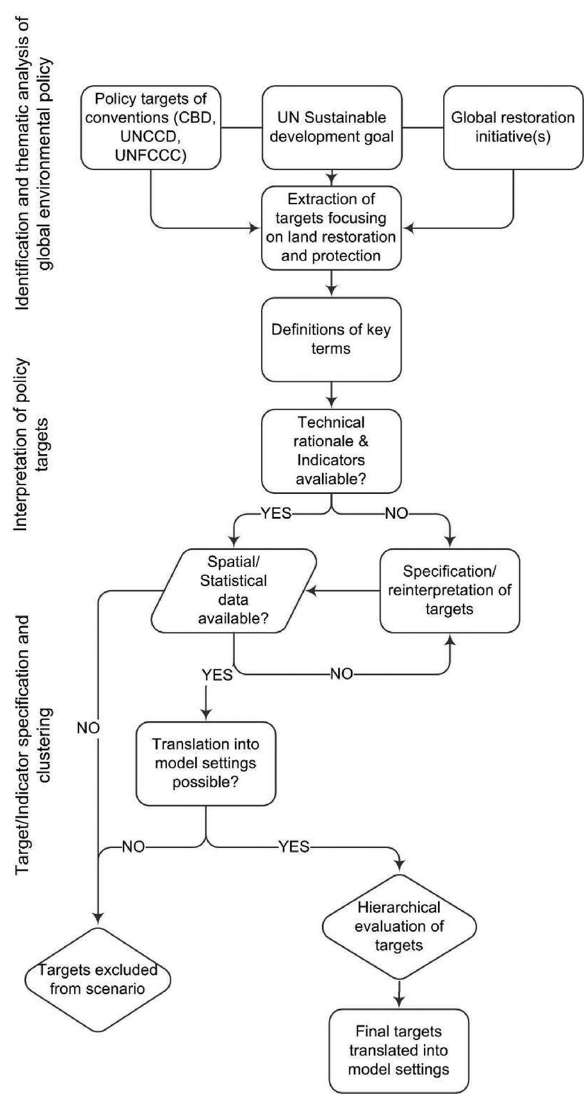

Fig. 1. Decision tree for including the global policy targets in the land system change model.

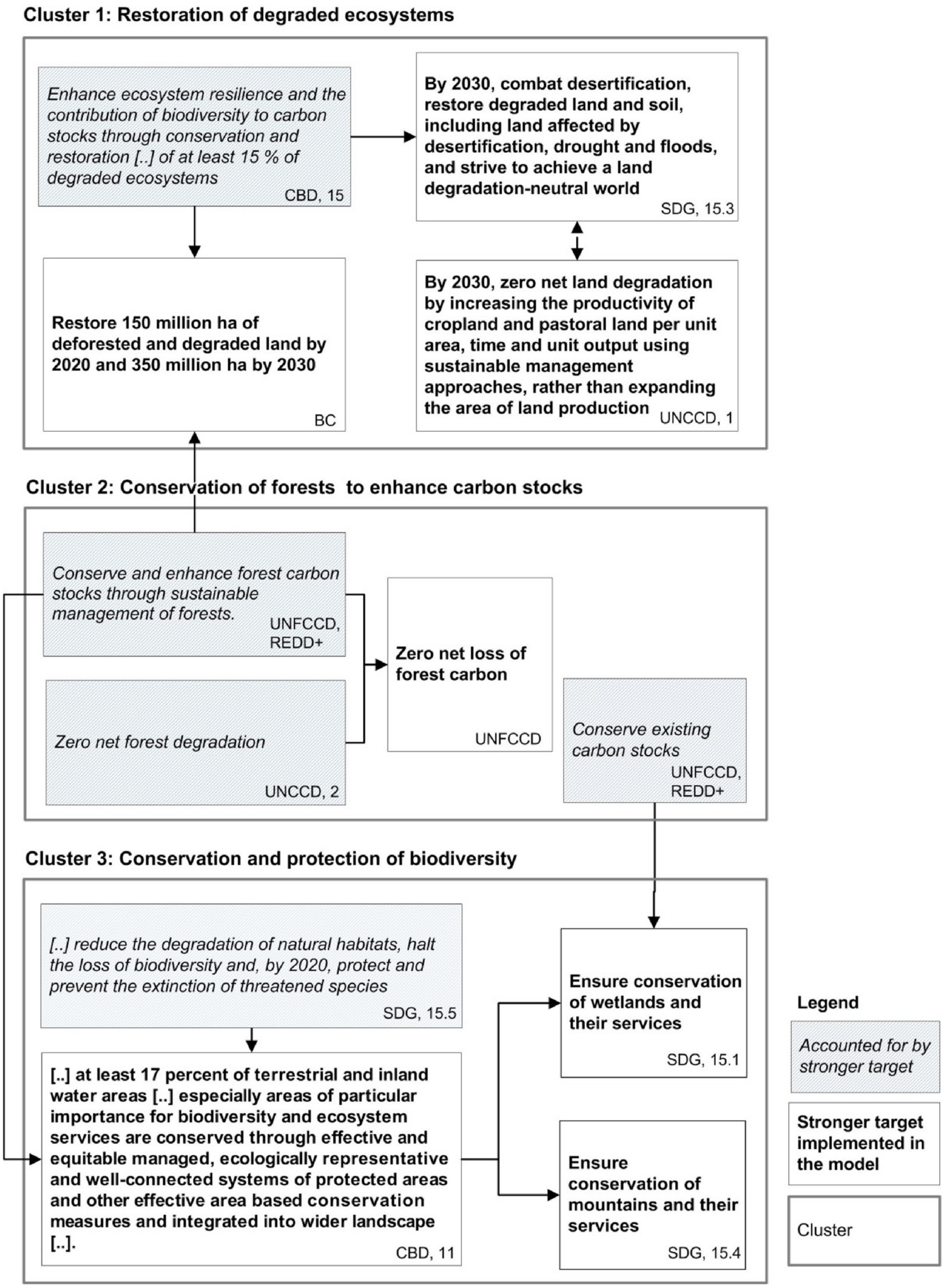

Fig. 2. Clusters of selected policy targets with reference to their underlying convention [Appendix A]. Targets that are shaded are overruled by stronger target(s) which are indicated in bold font. Arrows connect targets, whereas the larger boxes represent clusters.

After selection, remaining targets were clustered to identify overlap or conflict in their implementation. The targets addressed three main areas of interest: (1) the restoration of degraded ecosystems, (2) the conservation of forests, in particular to enhance carbon stocks, and (3) the conservation and protection of biodiversity. The clustering also helped to identify the hierarchical importance and strength of the targets and the potential to create synergies between them (Fig. 2). These clusters and their underlying targets were then implemented in the CLUMondo model (Section 3.2).

2.2. CLUMondo

To model the influence of the targets on land system change we used CLUMondo (van Asselen and Verburg, 2013). CLUMondo is a dynamic and spatially explicit model that uses land system types as modelling unit. In its global application, land system change is simulated at a spatial resolution of 9.25 km (approx. 5 min at the equator). Land systems integrate land use and land cover (Ornetsmueller et al., 2016; van Asselen and Verburg, 2012). Land use is reflected by land management intensity and livestock density/composition. Land cover types distinguished are tree cover, cropland, grassland, bare land, and built-up area. Cropland includes both annual and permanent crops (van Asselen and Verburg, 2012) for both food and non-food purposes. No distinction between irrigated and non-irrigated cropland was made.

The composition of land systems, as well as their management intensity, differs between land system type and region. Land system types range from specialized systems, such as land systems dominated by a single land use (i.e. intensive or extensive cropland systems), to mosaic land systems that combine multiple land uses, such as cropland, grassland and livestock (van Asselen and Verburg, 2012). Consequently, specialized land systems can produce large amounts of a specific goods or services, while mosaic land systems can contribute to meet multiple demands (multi-functional). Mosaic cropland systems have an average cropland cover of 30–35% and are subdivided based on their share of tree cover into mosaic cropland and forest systems (~35% tree cover) and mosaic cropland and grassland systems (~5% tree cover). A shift from a mosaic land system to a land system dominated by one land use type is referred to as land use specialization.

Land management is reflected in livestock density and agricultural intensity. In general, livestock density is lower in cropland with few livestock (< 100 heads of bovines, goats and sheep per km²), and higher in croplands with bovines' goats and sheep (> 100 heads). Agricultural intensity is expressed as efficiency of agricultural production. This efficiency ratio is based on global maps that were constructed based on stochastic production functions, that represent the maximum yield of major crop types (maize, wheat and rice), given environmental conditions (Neumann et al., 2010). The efficiency indicates the fraction of this maximum yield achieved in a certain location. Extensive systems have an efficiency of < 0.4, intensive systems of > 0.7 (Eitelberg et al., 2016).

We use the land system map initially developed by van Asselen and Verburg (2012) that was later adapted by Eitelberg et al. (2016) to limit livestock composition to bovines, goats and sheep, excluding pigs and poultry. The model uses 24 model regions [Appendix C, Figure C13] for which demands for land-based goods and services are translated into a spatial allocation of land systems.

CLUMondo allocates land systems in response to competing demands for goods and services, as well as location suitability and conversion rules that represent legacy effects, time-lags, specific land change trajectories and land use policies. Each land system can produce several goods and services that contribute to fulfilling societal demands. In meeting demands for a particular service, land systems that are able to provide more of that service are given a competitive advantage. However, depending on the scenario conditions, a preference for a specific system may be given while other systems are excluded as an option to meet that demand. Location suitability for different land systems is based on empirical relationships between current distributions of land systems and socio-economic and biophysical location factors. While some of these factors remain constant over time (e.g. elevation), others can change (e.g. precipitation, temperature) leading to changes in location suitability.

Policies or spatial restrictions in a scenario can influence the location suitability for a specific land system or can restrict land use conversions completely. For example, restoration policies can favor specific land systems for the restoration of degraded areas or can fully restrict land system change in areas important for biodiversity. Furthermore, conversion resistance indicates the difficulty (e.g. cost) of changing the existing land system at a location and can differ between scenarios to reflect policy incentives, restrictions, available technology or societal attitudes. The simulated allocation of land system change is thus a function of the differential location suitability for different land systems, the current land use, conversion or exclusion restrictions, and the competitive advantage of the different land systems in fulfilling demand for goods and services (Fig. 3). The numerical algorithm of the model solves this by matching the land system allocation with the externally specified demands. Documentation of the model and its open-source code are available at: www.environmentalgeography.nl.

2.3. Shared socio-economic pathways

The Shared socio-economic pathways (SSPs) were used as building blocks for the scenarios. The SSPs describe five different directions in socio-economic development (O'Neill et al., 2014) from which projected impacts on land use, energy and emissions have been assessed by different integrated assessment models (Riahi et al., 2017). For this study, we use data on (i) projected demands on land use and (ii) crop productivity that were assessed by the IMAGE model (Stehfest et al., 2014) at the level of world regions. We focused on two of the SSPs: The Sustainability (SSP1) and the Middle of the Road (SSP2) scenario. These represent a good reference as they respectively represent a frequently used baseline (SSP2) and a scenario aimed at sustainability transformations (SSP1) but without the explicit incorporation of land restoration and protection targets. As an input to CLUMondo, we used land demands for crop production, livestock and urban area for each world region. Crop production includes tons of human food and animal feed crops; livestock is expressed in units of bovines, goats and sheep. Projected changes in crop productivity and livestock production due to technological innovation were incorporated as an endogenous factor in calculating annual changes in crop production, consistent with the IMAGE model runs. Efficiency increases for urbanization were added according to the SSP narratives [Appendix B]. In addition, we calculated potential climate change impacts on crop productivity and added this factor to the total crop production efficiency [Appendix B]. Climate change was also taken into account by including precipitation and temperature as dynamic drivers of location suitability and in determining suitability for cropland in line with the representative concentration pathway (RCP) 4.5 (Hijmans et al., 2005) or the equivalent Special Report on Emissions Scenario (SRES) B1 (IPCC, 2000) for both the Sustainability and the Middle of the Road scenario [Appendix B].

3. Model implementation

3.1. Implementation of reference scenarios

The Sustainability scenario follows a sustainable pathway of socio-economic development that is characterized by increased commitment to achieve development goals (O'Neill et al., 2014). In CLUMondo this scenario is driven by the demand for crop production, livestock, urban area and carbon storage. Demand for carbon storage was implemented by assuming a no-net-loss situation, where the total carbon content of all land systems is not allowed to fall below 2000 levels, similar to the implementation of Eitelberg et al. (2016). In addition, protected areas of the IUCN categories 1–4 (IUCN, 2013) were fully restricted from land use change to conserve biodiversity. The Sustainability scenario assumes restrictions on urban sprawl. Compact urbanization was modeled through prioritizing areas close to existing urban areas for further urban development, and by increasing the amount of urban land cover within the urban land system types (1% in 5 years).

In the Middle of the Road scenario, socio-economic trends do not shift markedly from historical patterns, with relatively low commitment to achieve development goals (O'Neill et al., 2014). In this scenario we limited demands to crop production, livestock and urban area. To account for trends in protected area management, IUCN categories 1–2 were fully restricted from land use change. For the IUCN categories 3–4 location suitability for natural land systems was increased to represent less-binding conservation incentives in these areas (IUCN, 2013). The Middle of the Road scenario does not restrict urban sprawl. Neighbourhood weight that governs the attraction of urban areas for new urbanization was thus lower for urban and higher for peri-urban areas [Appendix B].

3.2. Implementation of targets into Restoration and Protection scenario

The socio-economic context of the Sustainability scenario was used

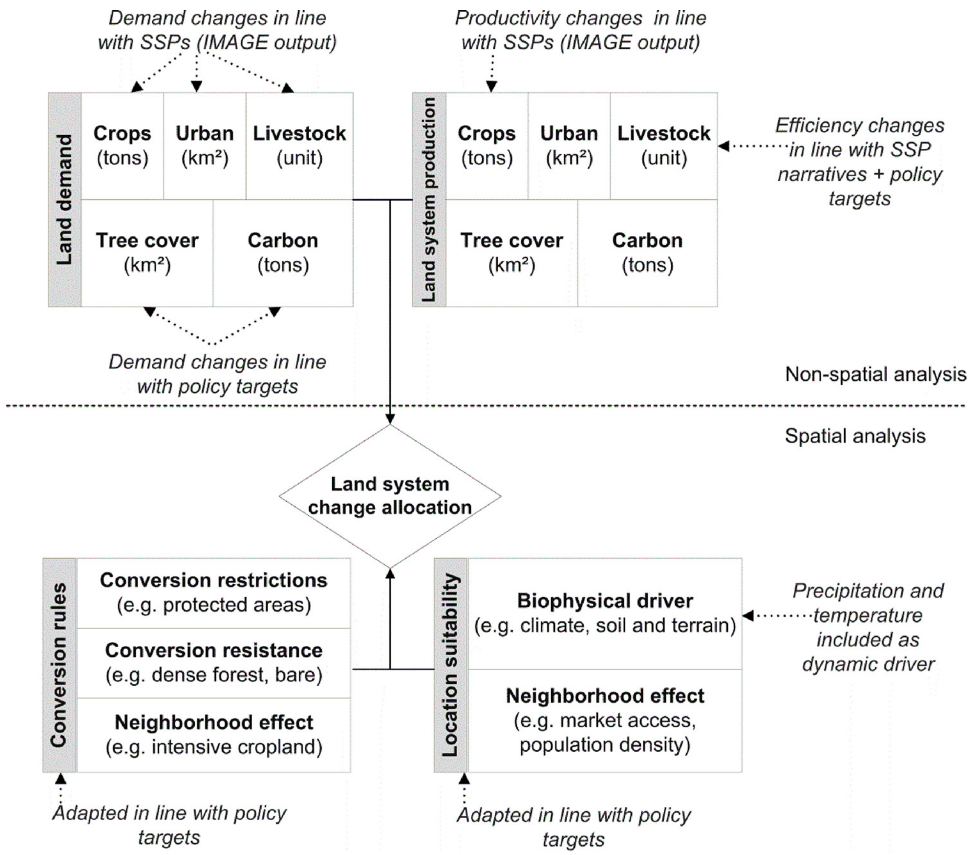

Fig. 3. Main elements of CLUMondo including key model settings. Dashed arrows indicate settings that have been adapted for the Restoration and Protection scenario.

Table 1
Average percentage change in demand from 2000 to 2050 for the different scenarios. Modeling regions were aggregated to world regions [Appendix C, Figure C13]. Demand for crops, bovines, goats and sheep (bgs), and urban area is based on modelling results from Stehfest et al. (2014); demand for tree cover and forest carbon is based on own calculations.

	Middle of the Road			Sustainability				Restoration and Protection				
World region	crops (t)	bgs (units)	urban (km²)	crops (t)	bgs (units)	urban (km²)	carbon (t)	crops (t)	bgs (units)	urban (km²)	trees (km²)	forest carbon (t)
Africa	305%	63%	275%	254%	4%	335%	0%	254%	4%	335%	23%	0%
China +	16%	−3%	53%	3%	−28%	61%	0%	3%	−28%	61%	6%	0%
Europe	44%	−3%	53%	23%	−45%	63%	0%	23%	−45%	63%	14%	0%
India/ Middle East	225%	75%	223%	198%	13%	242%	0%	198%	13%	242%	20%	0%
North America	61%	22%	104%	40%	−24%	97%	0%	40%	−24%	97%	6%	0%
Russia/ Stans	92%	48%	88%	104%	1%	117%	0%	104%	1%	117%	7%	0%
South America	147%	62%	94%	124%	8%	96%	0%	124%	8%	96%	7%	0%
South East Asia	113%	31%	159%	86%	−20%	175%	0%	86%	−20%	175%	5%	0%
Global average	**125%**	**37%**	**131%**	**104%**	**−11%**	**148%**	**0%**	**104%**	**−11%**	**148%**	**11%**	**0%**

as a baseline for the Restoration and Protection scenario and extended by the implementation of the global policy targets. The comparison between the Restoration and Protection scenario and the Sustainability scenario thus shows the relative influence of adding the restoration and protection targets to the model. The comparison with the Middle of the Road scenario shows the combined influences of the socio-economic pathway and the restoration and protection targets. The targets where implemented following the clusters and underlying target definitions identified in Section 2.1.

As a starting point we used land demands from the Sustainability scenario and adapted them to account for targets from **Cluster 1: Restoration of degraded ecosystems** and **Cluster 2: Conservation of forests to enhance carbon stocks** (Fig. 2). To account for **Cluster 1**, a demand for tree cover was added in line with the target of the Bonn Challenge to "*restore 350 million ha deforested and degraded land by 2030″* (IUCN, 2017b). Following the definition of forest landscape restoration, this target refers to the restoration of mosaic and dense forest that have been degraded by human influence (Potapov et al., 2011). As these forest systems have a tree cover of about 20–70%, we assume that 50% of the total target translates into actual tree cover increase. This target was downscaled by assuming restoration of at least 15% of total forest restoration opportunity area per region, not considering priority regions. This links to the Aichi target 15 that calls for restoring 15% of degraded ecosystems (CBD, 2011). For regions that committed more than 15% of their restoration opportunity to date (IUCN, 2017b), we assumed that these commitments were met. Altogether, this results in a restoration target of 177 million ha until 2030. Between 2030 and 2050 the minimally required tree cover was kept stable (while being allowed to overshoot).

To account for **Cluster 2**, UNCCCD target: *"Zero net loss of forest*

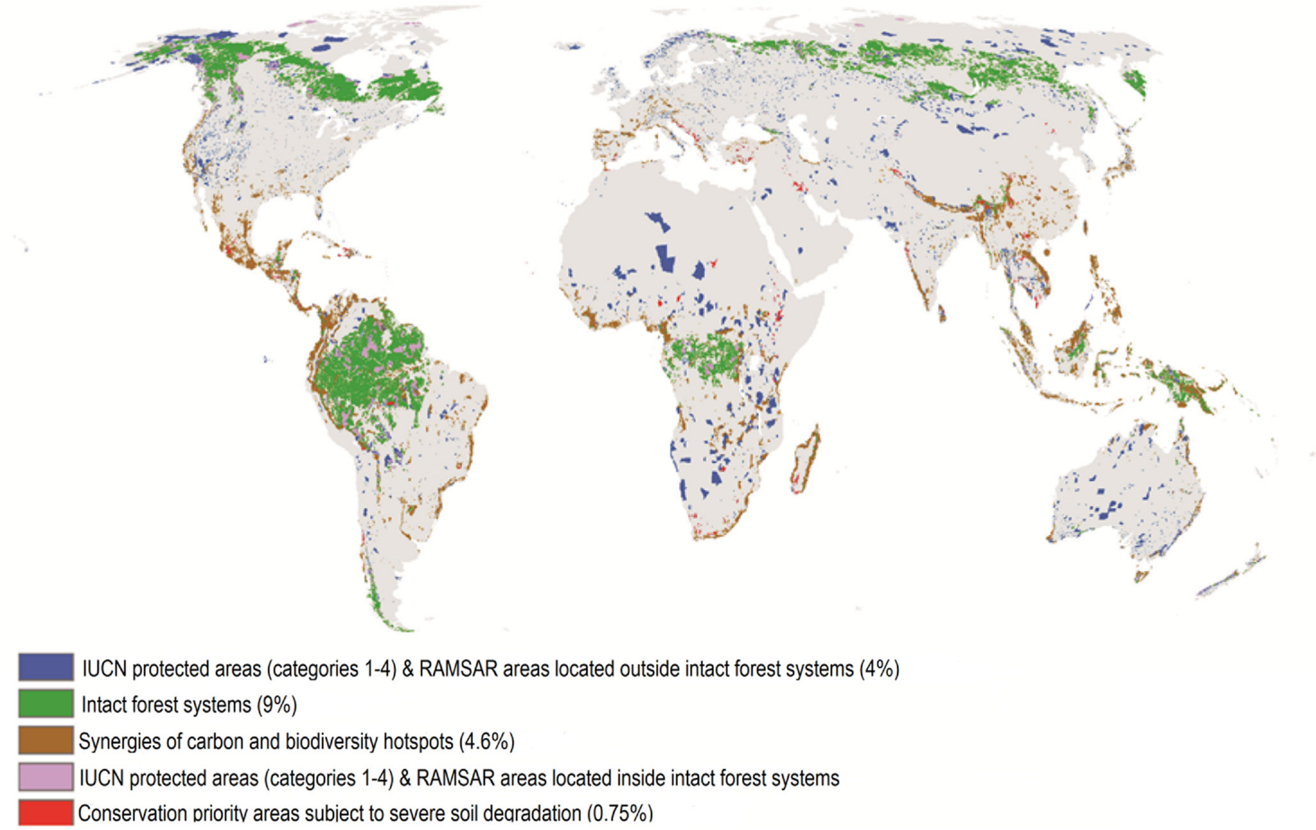

Fig. 4. Areas restricted from land use change for the conservation and protection of biodiversity and carbon storage; given as percentage share of terrestrial area. Original date of data source: IUCN protected areas: 2013, intact forest systems: 1990–2000, carbon hotspots: 2000, conservation priority areas: based on multiple datasets ranging between 2000–2013, RAMSAR areas: 2014, soil degradation: 1990.

carbon", carbon demand was specified as forest carbon demand meaning that only forest and forest mosaics were accounted for in meeting this demand. This demand was kept stable. Table 1 provides an overview of the changes in demands for the different scenarios.

The remaining targets of **Cluster 1** and targets of **Cluster 3** do not directly reflect area targets but rather incentives and restrictions on conversions. These targets were implemented through adapting the location suitability for specific land systems and by defining conversion restrictions. This required prior spatial analysis to indicate where these changes apply (Fig. 4). Reference to spatial data can be found in Appendix B.

To implement the forest restoration targets of **Cluster 1** we increased location suitability for mosaic forest systems in areas providing mosaic restoration opportunities, and for dense forest in areas providing wide-scale restoration opportunities (Potapov et al., 2011) respectively, increasing tree cover density in these areas. To implement the UNCCD target 1 *"zero net land degradation"*, we limited agricultural expansion into adjacent ecosystems and areas with degraded soils using the model's neighborhood algorithm to stimulate intensive cropland systems in areas with limited land availability. To avoid desertification caused by agricultural intensification, we decreased location suitability for medium, and intensive cropland systems in dryland regions with an aridity index < 0.2, (UNCCD, 2014), as well as in areas under severe soil degradation according to the Global Assessment of Human-induced Soil Degradation (GLASOD) (Oldeman et al., 1990). To avoid that land abandonment of less productive land leads to land degradation and desertification, the likelihood of conversion from all non-bare to bare land systems was decreased. At the same time, the conversion resistance of bare areas was decreased, reflecting increased restoration investments in these areas.

To account for the SDG target 15.3 on the restoration of degraded land and soil in drylands we increased location suitability for natural land systems in dryland areas subject to severe soil degradation (UNCCD, 2014; Oldeman et al., 1990). This reflects the increas ed probability for re-growth of natural vegetation.

To implement **Cluster 3**:**Conservation and protection of biodiversity**, CBD target 11 and SDG target 15.1, protected areas of IUCN categories1–4 (IUCN, 2013), wetlands of international importance (RAMSAR, 2014), and intact forest landscapes (Potapov et al., 2008) not covered by the IUCN protected area network were fully restricted from land use change. This was done under the rationale that protected areas under IUCN categories 1–4 are of particular importance for biodiversity and ES provision (IUCN, 2016). Wetlands and intact forest landscapes were protected for the same reason but are additionally important for storing most of the soil and above ground carbon biomass. Areas to expand the protected area network were assessed with the aim to create maximum synergies between (i) protected areas of IUCN categories 5–6 managed to maintain cultural landscapes and nature conservation, (ii) carbon hotspots (Ruesch and Gibbs, 2008), as well as (iii) global conservation priority areas (as an indicator for biodiversity and threatened species) (Pouzols et al., 2014). In addition, global conservation priority areas subject to severe soil degradation were considered to address the SDG target 15.5 to reduce the degradation of natural habitat and the extinction of threatened species (UN, 2015). Together, these areas result in a global protected area network covering 17.8% of the terrestrial area that was fully restricted from land use change (Fig. 4). The SDG target 15.4, addressing the conservation of mountains and their services, was implemented by increasing location suitability for natural land systems currently located in mountain regions (covering 11% of the terrestrial surface in 2002) (UNEP-WCM, 2002).

Ecosystem services from productive croplands were not mentioned

Table 2
Changes in land systems and land system architecture from 2000 to 2050, under the different scenarios (modeled results). MR: Middle of the Road, S: Sustainability, RP: Restoration and Protection.

Land system architecture	Land system	Land management	Percentage change to 2000		
			MR	S	RP
Natural land systems	Dense forest	*nature*	9%	29%	34%
	Mosaic grassland & forest	*nature*	−19%	−34%	0%
	Natural Grassland	*nature*	29%	51%	72%
	Mosaic grassland & bare	*nature*	9%	2%	19%
	Total		**−1%**	**−3%**	**19%**
Mosaic forest and agriculture	Open forests; few livestock	*extensive agri*	−27%	6%	9%
	Mosaic cropland, ext.& forests; few livestock	*extensive agri*	−22%	54%	36%
	Mosaic cropland med. int.& forest; few livestock	*extensive agri*	−56%	−49%	25%
	Mosaic cropland int. & forest; few livestock	*intensive agri*	35%	5%	24%
	Open forests; few livestock	*intensive agri*	−25%	4%	14%
	Total		**−27%**	**6%**	**9%**
Mosaic grassland and agriculture	Mosaic cropland & grassland; bovines, goats & sheep	*extensive agri*	41%	−62%	−84%
	Mosaic cropland ext. & grassland; few livestock	*extensive agri*	−69%	−16%	−71%
	Mosaic cropland med.int. &grassland; few livestock	*intensive agri*	−79%	−80%	−88%
	Mosaic cropland int. & grassland; few livestock	*intensive agri*	−29%	−68%	−59%
	Grassland, few livestock	*extensive agri*	−17%	−35%	−54%
	Total		**−27%**	**−45%**	**−62%**
Extensive cropland	Cropland ext.; few livestock	*extensive agri*	0%	11%	−72%
	Cropland ext.; bovines, goats & sheep	*extensive agri*	−69%	−92%	−98%
	Total		**−26%**	**−29%**	**−82%**
Medium intensive, intensive cropland	Cropland med. int.; few livestock	*intensive agri*	−78%	−78%	−72%
	Cropland med. int.; bovines, goats, sheep	*Intensive agri*	82%	28%	−77%
	Cropland int.; bovines, few livestock	*intensive agri*	83%	72%	105%
	Cropland int.; bovines, goats & sheep	*intensive agri*	271%	46%	94%
	Total		**33%**	**−1%**	**9%**
Intensive grassland	Grassland; bovines, goats & sheep	*Intensive agri*	**705%**	**624%**	**319%**
Bare land systems	Bare	*bare*	0%	1%	−20%
	Bare; few livestock	*bare*	−16%	−9%	−27%
	Total		**−9%**	**−5%**	**−24%**
Urban, peri-urban	Peri-urban & villages	*urban*	145%	133%	118%
	Urban	*urban*	122%	125%	138%
	Total		**140%**	**131%**	**122%**

in the analyzed targets and the services produced by these land systems were thus not accounted for in the Restoration and Protection scenario. Full targets are given in Appendix A, Table 1A. For an overview of the land systems see Table 2. For a detailed description of the model implementation of the different scenarios see Appendix B. Data for the different scenarios was made available at www.environmentalgeography.nl.

Land system changes were simulated for all three scenarios. The year 2000 is used as a reference from which changes of the different pathways are measured until 2050.

4. Results

4.1. Global land cover and land system change

Fig. 5 visualizes global land systems in 2050 under the Restoration and Protection scenario and the land systems in 2000 that were used as a reference. These maps, as well as the simulation results for the Sustainability scenario and the Middle of the Road scenario [Appendix C, Figure C2, and C3], provided the basis for analyzing changes in land cover, land system architecture, and land management, presented in this section.

The implementation of policy targets in the Restoration and Protection scenario increases global tree cover by 14%; 3% more than was specified to meet the Bonn Challenge (Table 1). This equals a net increase of 4 million km^2 and a total tree cover area of 32.75 million km^2 by 2050. Gains in tree cover increase forest carbon by 10%, resulting in a total carbon stock of 547 Gt. Compared to the Sustainability reference scenario, tree cover increases much more (14% vs. 5%). Prioritizing forests for carbon sequestration increases carbon stocks twice as much as compared to the Sustainability scenario (10% vs. 4%). Increases in tree cover come at the cost of pasture (-6% vs. -1%) and bare land (-4% vs. -1%). Cropland decreases at similar extents as in the Sustainability scenario (-6%). Compared to the Middle of the Road reference scenario land cover changes are very different, showing opposing trends. In the Middle of the Road scenario tree cover decreases by 7% in favor of an increase in pasture (6%), and crop area (8%).

In the Restoration and Protection scenario, increases in tree cover and crop area are mostly allocated in mosaic systems of forest and agriculture. Mosaic forest and agriculture combine forest restoration and forest carbon demand with crop and livestock demand and are therefore prioritized in the Restoration and Protection scenario. In the Sustainability scenario, these mosaics increase as well, but to a lesser extent (Table 2). Differences between the Sustainability and the Restoration and Protection scenario are visible in Western Europe, South America and India (Fig. 6).

Land restoration targets increase natural land systems that otherwise decrease in the Sustainability and Middle of the Road scenario. In contrast to the reference scenarios, mosaic grassland and forest remain at similar levels as in 2000, while natural grassland and grassland-bare mosaics increase as a result of soil restoration. Avoided land abandonment and re-growth of these natural land systems in soil degraded areas reduces bare systems three times as much compared to the Sustainability and Middle of the Road scenario. Demand for forest carbon and wide-scale forest restoration increase dense forests to a greater extent compared to the Sustainability scenario. In the reference

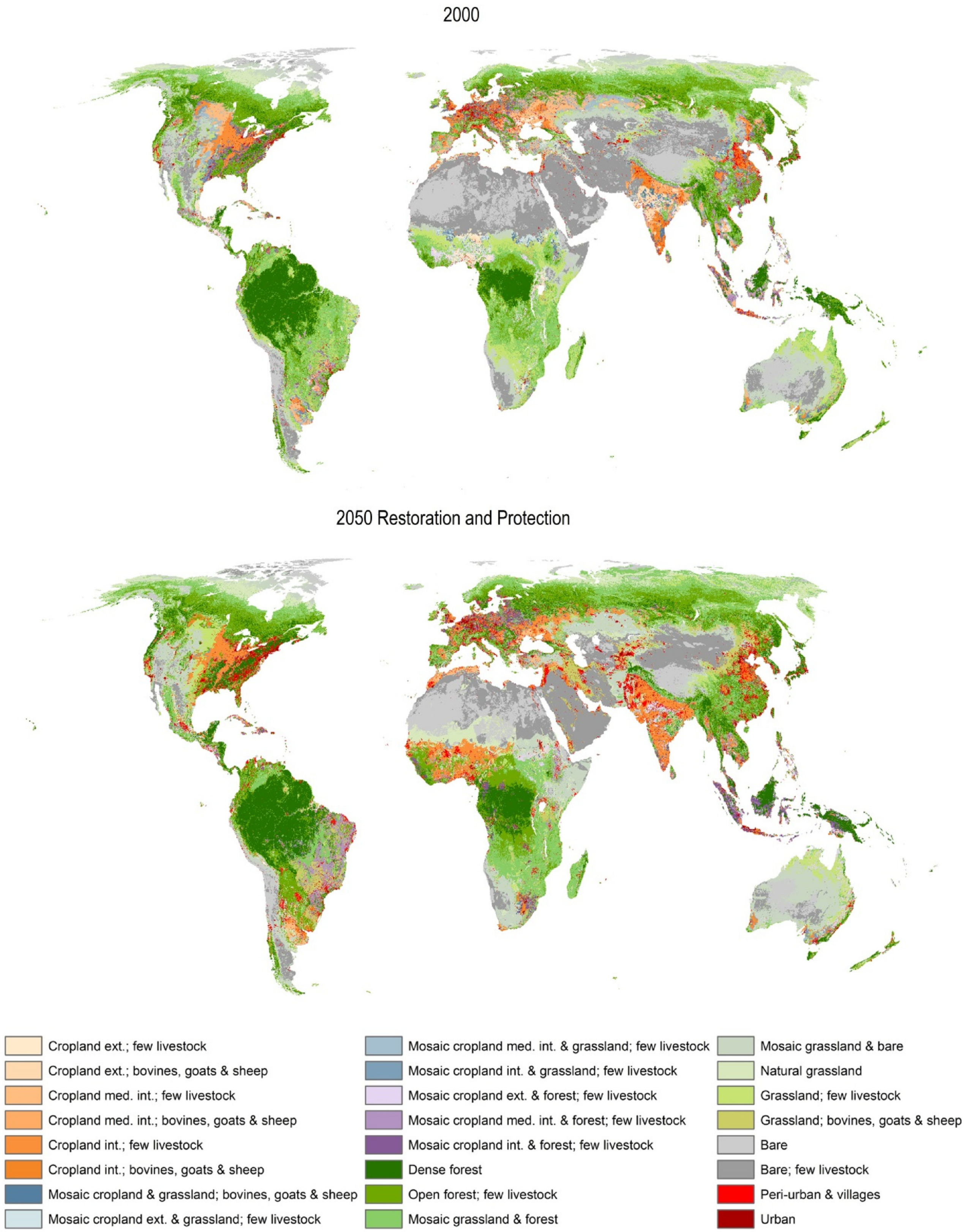

Fig. 5. Land systems in 2000 (reference) and in 2050 (modeled) under the Restoration and Protection scenario.

scenarios natural land systems decrease at the expense of grassland intensification (i.e. grasslands with bovines, goats and sheep), and urban expansion.

In the Restoration and Protection scenario, increase in forest-agriculture mosaics and natural land systems is associated with cropland intensification in remaining production areas. Efficiency increases in crop production and the allocation of crop demand into mosaic forest and agriculture reduces extensive cropland by 80% (Table 2). The demand for land restoration and protection thus clearly affects also other agricultural areas by strongly pushing intensification locally.

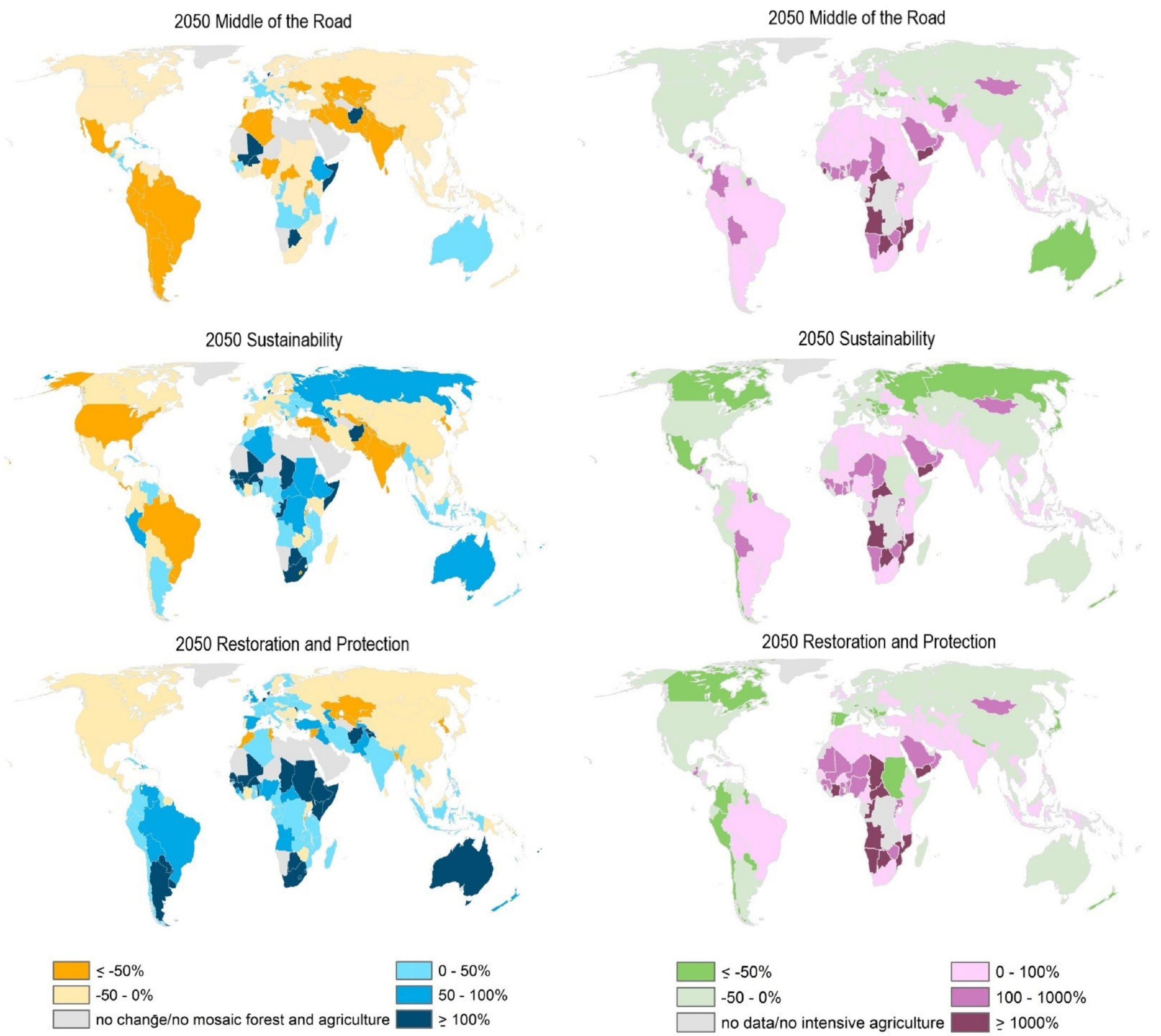

Fig. 6. Percentage change between 2000–2050 of mosaic forest and agriculture (left) and agricultural intensity (right), aggregated from pixel level to country level (modeled results).

Compared to the reference scenarios, however, the Restoration and Protection scenario leads to less agricultural intensification on a global scale due to lower grassland intensification. This can be explained by the greater allocation of livestock to extensive and semi-natural mosaic land systems. In several regions, the Restoration and Protection scenario results in a disintensification of agriculture, such as in Colombia, Peru and Spain (Fig. 6). In the Middle of the Road scenario, in contrast, growing demand for crop production and livestock is met predominantly by further intensification of cropland and grassland, while extensive and mosaic agriculture decrease. In this scenario, agricultural intensification results in higher land use specialization into crop- and grassland compared to the Restoration and Protection scenario where agricultural intensification also occurs in mosaic cropland systems.

The influence of the land restoration and protection targets on land system architecture is visualized for India (Fig. 7) and West and Central Africa (Fig. 8).

India observes among the highest tree cover change in the Restoration and Protection scenario (+ 87%) and the highest relative difference in tree cover change when compared to the Middle of the Road (-33%) and Sustainability scenario (-9%). Most tree cover is gained in the north and center of the region, where large areas of forest restoration opportunities exist. In these areas, forest restoration is integrated into mosaic forest and agriculture preventing land use specialization and forest losses, observed in the Sustainability, and Middle of the Road scenario.

West and Central Africa represents a region where the effects of the restoration and protection targets on local agricultural intensification are most visible (Fig. 8). These patterns contrast with the Middle of the Road and Sustainability scenario where agriculture remains dominated by extensive systems. Agricultural intensification results in increased land use specialization with almost all agriculture allocated to intensive cropland, and almost all natural and semi-natural land systems spared for land and forest restoration.

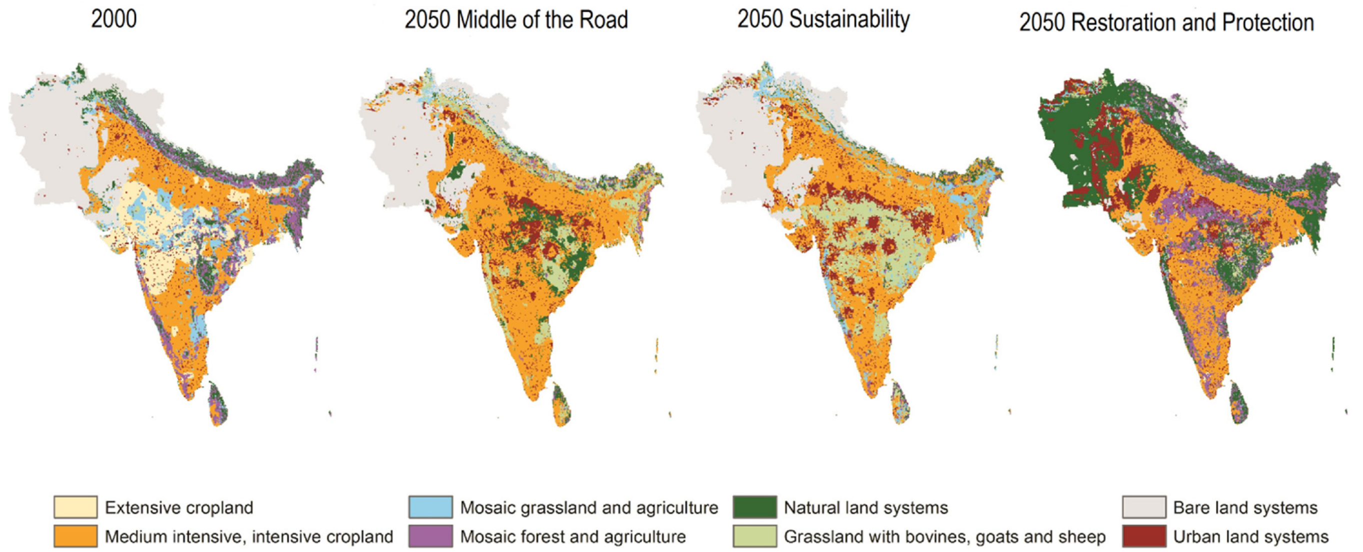

Fig. 7. Changes in land system architecture in India between 2000 (reference) and 2050 (modeled) under the Middle of the Road, Sustainability, and Restoration and Protection scenario.

4.2. Importance of protection targets for the conservation of biodiversity and carbon hotspots

Without the implementation of the policy targets to conserve and protect biodiversity and carbon stocks (Fig. 2, Cluster 2 and Cluster 3), several hotspots of biodiversity and carbon would be lost in 2050 (Fig. 9). Under the Middle of the Road scenario, this applies to 3% of the full global coverage of conservation areas (23.5 million km^2), protected in the Restoration and Protection scenario; in the Sustainability scenario to 2.7% of this area. In the Middle of the Road scenario, most of these losses derive from land use conversions to medium intensive/ intensive agriculture (44%) and to extensive agriculture (25%). In the Sustainability scenario, this conservation area is converted to extensive agriculture (37%) and to natural land systems (28%). In both scenarios, loss of conservation areas is observed in the Himalayas in India, in Papua New Guinea, along the wetlands of the East coast of South Africa and in Central- and South America, among other regions. Most of these areas provide hotspots of both biodiversity and carbon storage. A key difference between scenarios is the higher relative loss of intact forest landscapes of total loss in conservation area, under the Sustainability (-14%), as compared to Middle of the Road scenario (-7%), in areas such as Russia and North America.

For all scenarios we assessed the loss of natural land systems located in mountain regions. In the Restoration and Protection scenario these land systems were not fully protected from land use change but conserved by increasing their location suitability. Most of these systems remained intact, with a loss of 8% (from a total initial coverage of 14.5 million km^2). Without conservation of natural land systems in mountain regions, a loss of 19% (Middle of the Road) or 27% (Sustainability) is expected, largely due to grassland intensification and the conversion from dense to open forest. In 2050, natural land systems in mountain regions and conservation areas cover 28% of the global land area. In the reference scenarios, these areas remain at coverage of 22.8% (Middle of the Road) and 22.1% (Sustainability).

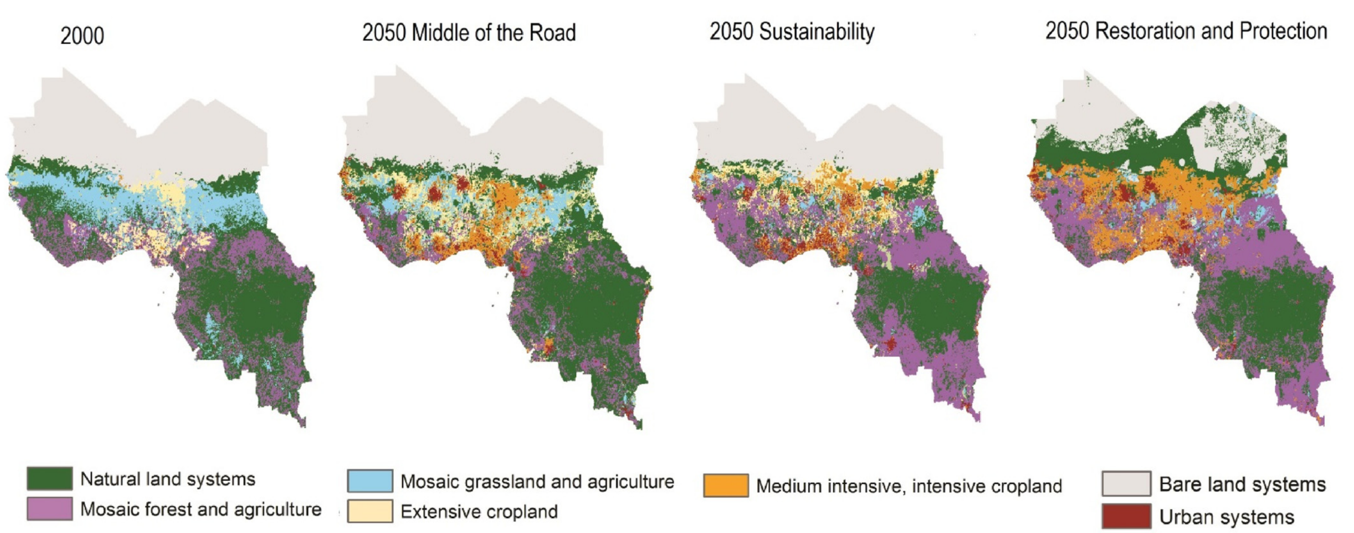

Fig. 8. Changes in land system architecture in West and Central Africa under the different scenarios. In the Restoration and Protection scenario, mosaic forest and agriculture is fully represented by open forests with few livestock. For global scale maps see Appendix D.

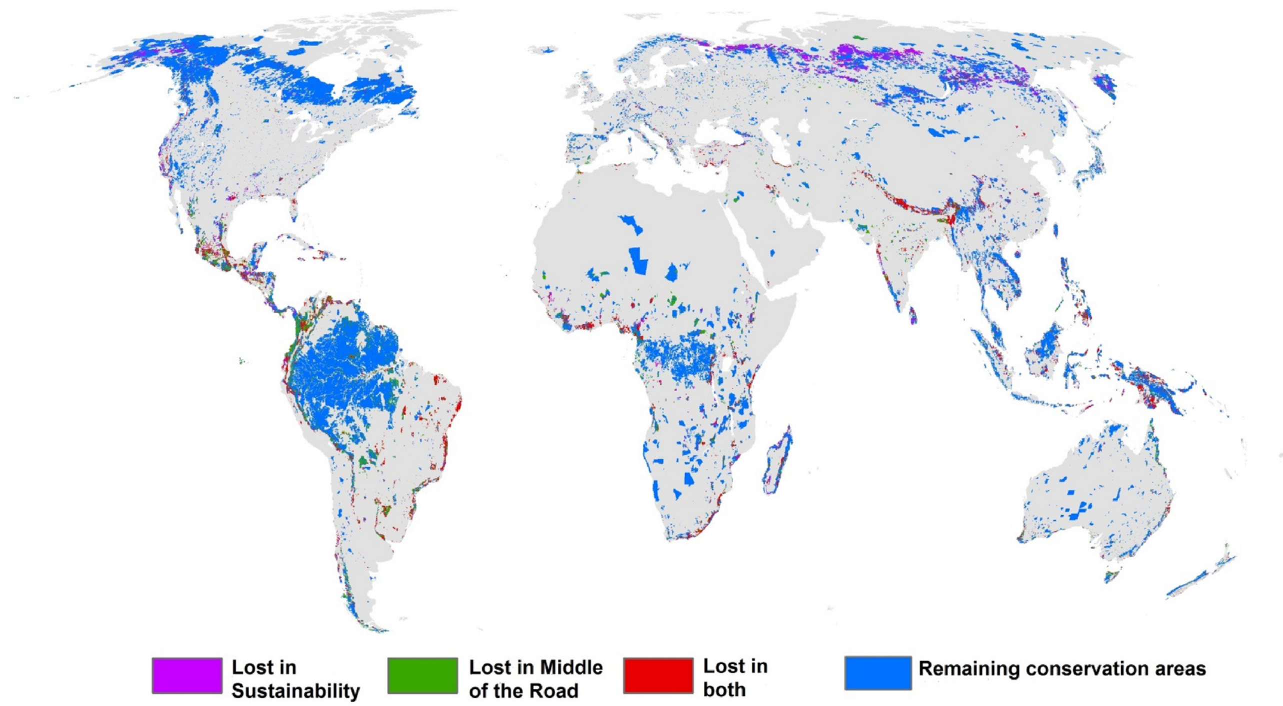

Fig. 9. Conservation areas, protected from land use change under the Restoration and Protection scenario that were lost through land use conversions in the Sustainability, Middle of the Road and in both scenarios (modeled results).

5. Discussion

5.1. Comparison of simulated results with reference scenarios

Our simulation, when compared to the reference scenarios provides an insight into possible effects of the implementation of global policy targets in combination with other land change pressures. The resulting land system architecture strongly differs from the Sustainability and Middle of the Road reference scenarios, even while the Sustainability scenario is normally used as an example of sustainable development. Implementation of the global policy targets had a positive effect on the patterns of land system architecture and land use management in most world regions. Increases in forest-agriculture mosaics reduced land use specialization and resulted in, overall, less agricultural intensification as compared to the reference scenarios. In regions where agricultural intensification was necessary due to increasing agricultural demand (i.e. Brazil and India), intensification within mosaic forests and agriculture fulfilled demand for agricultural production, forest restoration and carbon storage. Additional intensity increases of cropland reduced agricultural expansion and allowed to spare land for protected areas, dense forests and other natural land systems. The only region for which contrasting patters were observed is West and Central Africa. Here, high demand for cropland and urban development only allowed partly for the integration of forest restoration into mosaic land systems. Large scale intensification of agriculture was required to meet remaining crop demand. While such land sparing reduced pressure on valuable conservation areas, it may decrease ES and biodiversity embedded in agricultural systems (Power, 2010). We found that carbon was higher in soils of intensive and medium-intensive agriculture compared to extensive agriculture; agricultural intensification could thus be associated with losses of carbon.

Our results show that meeting restoration and protection targets could come at the expense of grassland in agriculture mosaics. Concerns on the loss of grasslands related to climate mitigation and reforestation have been widely discussed (e.g. Parr et al., 2014; Wilson et al., 2016). Our results show that loss of grassland-agriculture mosaics was an important issue in all scenarios. Especially under the reference scenarios a lot of these mosaics were lost through either grassland intensification or land abandonment. In the Restoration and Protection scenario, the targets had a positive effect on the area of natural and semi-natural grassland mosaics. Grassland biomes have received little consideration in the global environmental policy agreements (Veldmann et al., 2015; Bond, 2016). As shown by this study, neglecting these biomes in research and global environmental policy could pose threats to biodiversity and human well-being (Lehmann and Parr, 2016).

5.2. Importance of land management and demand changes to meet restoration and protection targets

If socio-economic trends continue similar to historical patterns without major improvements in land management (Middle the Road scenario), we can expect a greater loss of nature to highly specialized and intensively managed land uses. Land use specialization can pose threats to human well-being by reducing the delivery of public goods of agricultural landscapes (Landis, 2017). Simplification of landscape structures through a focus on single commodities has shown to cause ecological disruptions and losses of ES (Flynn et al., 2008). In particular, conversion to intensive grassland has been shown to reduce soil organic carbon stocks, agro-biodiversity, and to increase erosion risk (Modernel et al., 2016). In the reference scenarios, many open forests were replaced by intensive grassland in areas that provide high value for biodiversity. In the Sustainability scenario more than a third of intact forest landscapes and natural land systems in mountain regions were lost through grassland intensification. In the Middle of the Road scenario, grassland intensification was the dominant process in converting conservation areas.

The changes observed in the reference scenarios emphasize the importance of targeted land management in line with the environmental policy targets. This entails, on the one hand, the wide-scale restoration of degraded and currently unproductive land, and on the other hand the incorporation of trees into mosaic land systems (e.g.

agro-forestry) along with the intensification of crop and pastoral land in areas already in use and suitable of production (UNCCD, 2014). The combination of functions at landscape level, has been often argued for given their potential role in diversification of local livelihoods, food-security and biodiversity protection (Scherr and McNeely, 2008). Such landscape approaches include wildlife-friendly farming, that combines high biodiversity with high yields in tropical forests (Clough et al., 2011), or integrated landscape management (Reed et al., 2016). Industrial models of agricultural intensification have had negative effects on the environment, such as nutrient runoff, soil erosion and habitat destruction (Foley et al., 2005; Power, 2010). To minimize trade-offs between agricultural intensification and other important ES, sustainable models of agricultural intensification will be highly important. Examples of such approaches include conservation agriculture (Busari et al., 2015), integrated pest management (FAO, 2018), or climate-smart agriculture (Campbell et al., 2014).

Our results also illustrate the importance of considering the drivers of land degradation. In the reference scenarios, pressures included grassland intensification, crop expansion, and inefficient urban development, driven by population and lifestyle changes and associated changes in consumption demand, as well as increases in crop production as a result of technological innovation. In the Sustainability scenario, increased crop productivity and compact urbanization allowed the reduction of extensive croplands to a larger extent than in the Middle of the Road scenario, where these efficiency gains were absent. Likewise, a global decline in demand for livestock products in the Sustainability scenario resulted in less land use specialization and less agricultural intensification, compared to the Middle of the Road scenario. The importance of human diets in determining options to meet growing food demand, while protecting forests from deforestation, was shown in a study by Erb et al. (2016). This study found reduced consumption of livestock products to be the most powerful factor in meeting both food security and forest protection, outweighing factors such as changes in crop yields and cropland suitability. A focus on tackling these behavioral drivers is thus an essential factor to limit additional land degradation in the future and requires greater consideration in current environmental discourse and national action plans (Scherer and Verburg, 2017).

5.3. Methodological issues

The translation of the global policy targets into model settings was challenged by vague target definitions and limited data availability. Most of the targets on land degradation and restoration referred to the reduction and halt of land degradation, in particular in drylands. As an indicator of the state of global land degradation, the Normalized Difference Vegetation Index (NDVI) was proposed by the UNCCD. However, we decided against using this indicator, given difficulties to measure soil degradation through NDVI in scarcely-vegetated, bare areas (Higginbottom and Symeonakis, 2014). Instead we quantified land degradation by the extent and severity of soil degradation according to expert reporting (Oldeman et al., 1990) and by forest degradation based on satellite data (Laestadius et al., 2011). High uncertainty is involved in these data: land degradation is context dependent and subjective, given that the state of land is depending on the initial function it had for the user (Gibbs and Salmon, 2015; Hobbs, 2016). Further uncertainties were related to the implementation of targets that addressed specific sectors, ES or user groups. For example, the Aichi Biodiversity target 11 focuses on the restoration and conservation of essential ES that contribute to health, livelihoods and well-being, in particular to meet the needs of women, indigenous, local communities, and the poor and vulnerable (CBD, 2011). While we were able to account for the restoration and conservation of some essential ES (i.e. food production, biodiversity), the specific implications on described user groups is unclear.

5.4. Feasibility of targets

This study showed that the implementation of global policy targets on land restoration and protection is feasible under the conditions assumed in a scenario of sustainable socio-economic development (SSP1). In our simulation, both global and regional demands were met by a combination of land sharing through mosaic land systems and land sparing of marginal land for the protection of biodiversity and carbon stocks. The only model region for which the full set of targets could not be implemented was Indonesia. In particular, the protected area target (i.e. CBD, Aichi target 11) posed an enormous land demand to this region. Considering global conservation priority areas, biodiversity-carbon hotspots and designated protected areas, almost half of the region is eligible for protection (48%). In addition, 18% of the region is covered by forest restoration opportunity areas. In light of the large population with growing demand for crop production and housing in this region, we had to limit the area designated to conservation areas to only cover the biodiversity-carbon hotspots, equal to 20% of the region [Appendix B]. This modified target lead to the loss of intact forest landscapes in Papua/Papua New Guinea, equivalent to 2% of the global intact forest area. Forest restoration targets, however, increased tree cover to an extent of 60% of the region in 2050, representing the largest share of tree cover in any region of the world.

How the implementation of restoration and protection targets looks in real world, is highly context dependent, depending on among other factors, other competing land demands, biophysical characteristics and institutional capacities. Land restoration can provide opportunities to increase the provision of ES and to conserve remaining biodiversity. But it can also result in potential conflicts, especially if only single ES are considered (Bullock et al., 2011). This is also demonstrated for West and Central Africa, where the restoration and protection targets lead to an increase of mosaic and natural land systems in one area, but to intensification of agriculture elsewhere. To reduce trade-offs between different ES and biodiversity and to meet the needs of different stakeholder groups, incentives, such as Payments for Ecosystem Services will be essential to compensate for the maintenance and provision of ES across regions. Further efforts to decrease demand for land (i.e. decreasing consumption) will be necessary, as under the Sustainability scenario already strong dietary changes are assumed.

Feasibility and success of land restoration will also be dependent on the level of forest and soil degradation, residual vegetation and desired restoration outcomes (Chazdon, 2008; Hobbs et al., 2009). The role of cropland in meeting land restoration and protection targets has only received a marginal role in environmental policy (beside its role in agro-forestry systems). This excludes a major avenue for land restoration through the restoration of ES, especially in productive croplands. Even though the UNCCD land degradation neutrality goal emphasizes the need for agricultural intensification by using sustainable management approaches (UNCCD, 2014), the contribution of croplands to the provision of ES, such as watershed services, wildlife habitat, soil organic matter, biodiversity and water (Power, 2010; Tscharnke et al., 2005) has so far not been addressed explicitly.

On a global scale the Restoration and Protection scenario succeeded in setting aside 28% of the terrestrial area for the conservation and protection of biodiversity hotspots, carbon storage, and other ES. Gains in mosaic forest and agriculture, as well as natural land systems outside these ES hotspots, provided an additional 16% and 22% of the terrestrial area to contribute to nature conservation, climate mitigation and other ES. Recently, the UN and several international organizations, such as Conservation International and CBD, have welcomed an ambitious target of protecting half of the terrestrial area by 2050, in order to halt global species extinction while sustaining livelihoods (Nature Needs Half, 2017). If the sustainable development agendas and those of the other conventions are combined and synergies created, for example by encouraging and facilitating nature-inclusive (mosaic) agriculture alongside pure protection agendas, our findings suggest that this target might well be feasible under a pathway of sustainable socio-economic development. In this pathway demand for agricultural land use is strongly reduced, largely through efficiency increases of current agricultural land and changes in consumption behavior directed towards a reduction in livestock products. However, these findings should be interpreted with caution as also the remaining half of terrestrial area that is under intensive agricultural production will require sustainable management approaches. Our reference scenarios show that without such targeting or without drastic changes on the demand site, a far less green future of our globe is more likely.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gloenvcha.2018.08.002.

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